4.1 Introduction

4.1.1 Select the best available source

The first, and a key, step in providing safe drinking water is the selection of the best available source water. The most protected source waters will be the easiest and the cheapest to transform into safe drinking water. This is a general principle, and is one that has been known since the times of Plato (Whitlock, 1954). The Romans, for example, abandoned the river Tiber as a drinking water source in the third century BC and built 14 aqueducts in order to bring clean water from the surrounding hills. Principle, however, is not always translated into practice, although such oversights can have dramatic results, with a good example being provided by the Milwaukee Cryptosporidium outbreak (MacKenzie et al., 1994), which occurred in the spring of 1993 and was estimated to have caused illness in 400,000 people. The intake of Milwaukee's Howard Avenue drinking water treatment plant was located at a site in Lake Michigan that directly received the discharge of the Milwaukee River. The city's sewage treatment plant discharged into the Milwaukee River just upstream of the river mouth. Unsurprisingly, this made the intake of the plant vulnerable to fresh faecal contamination, especially during storm events. A study in the 1960's had already shown that this lake area contained high levels of faecal pollution (Schoenen, 2001). If this information had been used to select a more appropriate location for the intake point, or to redirect the sewage discharge, the contamination level during spring 1993 would very likely have
been significantly lower and perhaps a major outbreak would have been avoided.

In general, groundwater is better protected than surface water. Groundwater from deep aquifers is protected from pathogen contamination by the covering soil layers. Rain water or other water (such as from surface water infiltration, irrigation, sewer leakage etc.) that percolates through the soil can harbour pathogens but these are effectively removed by attachment to soil particles, die-off and biological processes (e.g. predation). Pathogen die-off during the extended time of travel from the surface through the ground to the point of abstraction in low permeability aquifers is also an important factor in reducing microbial risk. Deep groundwater from confined or semi-confined aquifers is therefore a preferred source for drinking water production. Shallower groundwater sources or groundwater that can be influenced by surface water will be more vulnerable to faecal contamination. Fine-textured soils (clay, silt) retain pathogens better than light-textured soils (sand). Soil types with a very coarse texture (fractured rock, sand and limestone, gravel) or cracks provide a relatively poor barrier against microbial contamination. Here, contact between pathogens and soil particles is less intense, leading to a lower attachment rate and greater penetration of the pathogens into the soil (REF – groundwater text).

Groundwater is not always available of suitable quality (because of salt, arsenic or fluoride content for example) or in adequate quantity. Additionally, groundwater abstraction requires drilling and pumping equipment that is not always available or sustainable especially in developing countries. Therefore, many communities rely on surface water as a source.

4.1.2 Catchment protection

Catchment protection is the second step in providing safe drinking water and where, for whatever reasons, source choice is limited it presents a key opportunity to minimise pathogen contamination. A major hazard to drinking water safety is presented by ‘precipitation’ events (rain, snowmelt), where large quantities of faecal material may be washed from the catchment into the water source, leading to the possibility of overwhelming treatment barriers and resulting in pathogen breakthrough into the finished water.

The importance of peak precipitation events is illustrated by a recent study in the USA. Rose et al. (2000) examined the relationship between waterborne disease outbreaks and precipitation in Pennsylvania and Colorado. The groundwater outbreaks in Pennsylvania occurred mainly in the lower river systems (Delaware, Schuylkill and Susquehanna River) where soil types are
sandstone, carbonate rock and semi-consolidated sand, soil types that are vulnerable to pathogen (especially virus) penetration. The surface water outbreaks were scattered. Both groundwater and surface water outbreaks in Colorado were mostly associated with the Upper River Platte watershed and tributaries that are influenced by large cities (Denver). By correlating the time of the outbreaks with the occurrence and intensity of precipitation in the month of the outbreak or the month(s) prior to the outbreak, they associated 20 - 40% of the waterborne outbreaks in Pennsylvania and Colorado to periods of extreme precipitation (highest 10% of precipitation), for both surface water and groundwater related outbreaks. A larger scale study, which examined outbreaks and precipitation data for a 47 year period found that 51% of waterborne outbreaks (excluding those related to recreational water, cross-connection or back siphonage) were preceded by extreme precipitation (Curriero et al., 2001).

Depending upon the nature of the catchment it may be possible to protect against such events by minimising possible contamination sources by, for example, removing grazing animals and diverting sewage overflows and discharge points. Where this is not feasible, a strategy for dealing with such events should be implemented. The remainder of this chapter looks at possible sources of contamination, the transport and survival of pathogens in surface and ground water and at the use of indicator parameters for informing management strategies.

4.2 Sources of faecal contamination

Humans, livestock and wild animals are all sources of faecal contamination, with pathogens being excreted in the faeces and occasionally urine. In general, human faecal wastes give rise to the highest risk of waterborne disease, since the probability of human pathogens being present is highest. Human enteric viruses (such as Norwalk-like caliciviruses, hepatitis A and E viruses, rotaviruses and enteroviruses) in water originate predominantly from human faecal material. Also *Shigella* spp., responsible for many waterborne disease cases and a large proportion of the deaths from waterborne disease (Traverso, 1996), is (almost) exclusively from human faecal origin. Other pathogens, such as *Campylobacter* sp., *Salmonella* spp. and *Cryptosporidium* sp., are present in both human and animal wastes. The probability of pathogens being present in these wastes depends on the presence of infected individuals that shed the pathogen.
4.2.1 Sources of surface water pollution

Surveys of pathogen occurrence in the sewage systems of urbanised areas show that pathogen presence in sewage and sewage effluents is the rule rather than the exception (Table 4.1). Treatment of sewage by sedimentation and activated sludge, for example, reduces the concentration of pathogens by 1-2 logs (90-99% reduction), but effluent still contains high levels of pathogens and indicator organisms. Even in (chlorine) disinfected sewage with low or no thermotolerant coliforms detectable in the effluent, viruses and protozoa are still likely to be present.

Table 4.1. Typical concentrations of enteric pathogens and index organisms in raw and treated domestic wastewater

<table>
<thead>
<tr>
<th>Microorganism</th>
<th>Raw sewage (numbers/litre)</th>
<th>Secondary effluent (numbers/litre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pathogens</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parasites</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cryptosporidium sp.</td>
<td>1 000 – 10 000</td>
<td>10 – 1 000</td>
</tr>
<tr>
<td>Giardia sp.</td>
<td>5 000 – 50 000</td>
<td>50 – 500</td>
</tr>
<tr>
<td>Viruses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enteroviruses</td>
<td>10 – 100</td>
<td>1 – 10</td>
</tr>
<tr>
<td>Norwalk like viruses</td>
<td>10 – 1 000</td>
<td>1 – 100</td>
</tr>
<tr>
<td>Rotavirus</td>
<td>10 – 100</td>
<td>1 – 10</td>
</tr>
<tr>
<td>Bacteria</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salmonella spp.</td>
<td>100 – 10 000</td>
<td>10 – 10 000</td>
</tr>
<tr>
<td>Index parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coliforms</td>
<td>$10^7$ - $10^9$</td>
<td>$10^5$ - $10^8$</td>
</tr>
<tr>
<td>Thermotolerant coliforms / E.coli</td>
<td>$10^6$ - $10^8$</td>
<td>$10^5$ - $10^7$</td>
</tr>
<tr>
<td>Enterococci</td>
<td>$10^6$ - $10^7$</td>
<td>$10^4$ - $10^6$</td>
</tr>
<tr>
<td>Clostridium perfringens</td>
<td>$10^5$ - $10^6$</td>
<td>$10^4$ - $10^5$</td>
</tr>
<tr>
<td>F-RNA phages</td>
<td>$10^6$ - $10^7$</td>
<td>$10^5$ - $10^6$</td>
</tr>
<tr>
<td>Somatic coliphages</td>
<td>$10^5$ - $10^7$</td>
<td>$10^5$ - $10^6$</td>
</tr>
<tr>
<td>Bacteroides phages</td>
<td>$10^4$ - $10^5$</td>
<td>$10^3$ - $10^4$</td>
</tr>
</tbody>
</table>


Stormwater discharges are a major cause of rapid deterioration in surface water quality. Storm events bring an elevation of turbidity, suspended solids, organic matter and faecal contamination into the drainage basin, caused by
urban and agricultural run-off, discharges from stormwater sewers and re-suspension of sediments. The microbiological quality of stormwater varies widely and reflects human activities in the watershed. Geldreich (1990) found that stormwater in combined sewers had more than 10-fold higher thermodurant coliform levels (8.9 × 10⁶ - 4.4 × 10⁷/l) than separate stormwater sewers (1.0 × 10⁵ - 3.5 × 10⁶/l).

Livestock are a well-known source of waterborne pathogens. Several outbreaks of cryptosporidiosis in the USA, Canada and UK have been associated with the contamination of water by run-off from livestock (Craun et al., 1998). At least one representative of pathogenic genera including Cryptosporidium, Giardia, Campylobacter, Salmonella, Yersinia and E. coli O157 are considered to be zoonotic. They are shed by infected livestock (Table 4.2) and may contaminate water sources and, thus, may be transmitted and infect humans.

Table 4.2. Percentage of animals shedding selected zoonotic pathogens

<table>
<thead>
<tr>
<th>Pathogens</th>
<th>% of animals shedding pathogens (no. of pathogens/kg wet weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cattle</td>
</tr>
<tr>
<td>Cryptosporidium sp.</td>
<td>20 - 90</td>
</tr>
<tr>
<td></td>
<td>(10⁶ - 10⁷)</td>
</tr>
<tr>
<td>Giardia sp.</td>
<td>57 - 97</td>
</tr>
<tr>
<td></td>
<td>(10⁶ - 10⁷)</td>
</tr>
<tr>
<td>Campylobacter spp.</td>
<td>1 - 10</td>
</tr>
<tr>
<td>Salmonella spp.</td>
<td>13</td>
</tr>
<tr>
<td>Yersinia sp.</td>
<td>1 - 10</td>
</tr>
<tr>
<td>Pathogenic E.coli</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Source: Erlandsen, 1994; Geldreich, 1996; Casemore et al., 1997; Medema, 1999; Schijven and Rijks, 2000.

Wild animals are another source of faecal contamination. In general mammals and birds (waterfowl) may shed human pathogens. Cryptosporidium parvum has been detected in a wide variety of wild mammals such as foxes, rabbits and a variety of rodents (squirrels, rats, mice, voles, hamsters) (Fayer et al., 1997). Cross transmission has been demonstrated between a number of these mammalian hosts (Fayer et al., 1990). Recent reports indicate that waterfowl may shed viable oocysts of C. parvum after ingestion of these oocysts (Grazcyk et al., 1996). Moreover, naturally infected Canada geese were shown to carry and shed the zoonotic strain of C. parvum (Grazcyk et al., 1998). Hence, birds that feed on sewage sludge or agricultural lands may ingest C. parvum oocysts and are a potential source of water contamination and zoonotic transmission.
Several waterborne outbreaks of giardiasis have been related to contamination of water by beavers and also by muskrats, another aquatic mammal with an even higher prevalence of *Giardia* sp. (Moore *et al*., 1969; Dykes *et al*., 1980). These reports, however, have been criticised, as the evidence provided was only circumstantial (Woo, 1984; Erlandsen, 1994). Other pathogens that have been implicated in waterborne illness, which also originate from wildlife are *Campylobacter* sp., *Yersinia* sp. and *Salmonella* spp. The carrier incidence of *Salmonella* spp. in waterfowl is generally 1-5%, but may be as high as over 20% in seagulls scavenging near sewage outfalls (Fenlon, 1981). *Campylobacter* spp. has been isolated from birds and rodents (Table 4.2).

In well-protected surface water catchments, upland reservoirs and mountain streams, wildlife may be the most important source of faecal pollution. For example, several cases in the Netherlands show that these systems are most at risk during late winter/early spring, when bird loads on the (partly frozen) reservoirs are high. When thaw sets in, the bird faeces that have collected on the ice enter the water, leading to a peak of contamination with *Campylobacter* or *Cryptosporidium* sp. and *Giardia* sp. (Medema *et al*., 2000a). In another study, Medema (1999) estimated that waterfowl contributed between 1 and 16% to the *Cryptosporidium* sp. concentration in reservoir water and 4 - 67% to the *Giardia* sp. concentration. However, as these (oo)cysts may not be pathogenic to humans, the significance of this source is a matter of debate.

### 4.2.2 Sources of groundwater pollution

Many practices with domestic wastewater and with livestock manure may lead to contamination of groundwater, these are summarised in Figure 4.1 and outlined in more detail below.

Septic tanks, cesspools, latrines and other on-site systems are widely used for wastewater storage and treatment. The water percolating from these facilities contains viruses, bacteria and parasites and may contaminate groundwater supplies. In the USA, septic tank systems rank highest in terms of the volume of untreated wastewater discharged into the groundwater and they are the most frequently reported source of groundwater contamination (Hagedorn, 1984). Sewers in the unsaturated zone may leak sewage into the soil, and it is likely that the extent of this problem is largely unrecognised. In the saturated zone, sewer breaks will result in groundwater contamination. During heavy rainfall, stormwater collection in sewers may increase the leak rate, leading to increased contamination.
There are several types of land application of waste or stormwater, including infiltration, overland flow, wetlands and subsurface injection. Several studies have shown that viruses can be found in the groundwater up to 30m beneath land application sites and can travel several hundreds of meters laterally from the application point (Keswick, 1984). In one case, viruses were demonstrated after heavy rainfall in a sampling site that was previously considered uncontaminated (Wellings et al., 1974).

Stormwater collected in sewers that also transport domestic wastewater can present a major problem. Other than direct discharges to water bodies (which clearly lead to contamination), it may also be disposed of by collection in basins and subsequent drainage to soil. This percolation may transfer pathogens to groundwater, as illustrated by Vaugh et al. (1978) who reported viruses in the soil 9 m below a stormwater basin.

Digested or composted sludges from sewage treatment plants are applied to cropland. These sludges contain viruses, parasites and bacteria (Bitton and Farrah 1980; Feachem et al., 1983). Although parasites and many bacterial pathogens are inactivated during thermophilic sludge composting, some viruses survive this treatment (Damgaard-Larsen et al., 1977). In field studies, no viruses could be found in the leachates of sludge disposal sites (Bitton and Farrah, 1980) and it has been suggested that the sludge/soil matrix is effectively retaining the viruses in the sludge. When groundwater tables are high, there may be direct contact between groundwater and sludge and this probably leads to groundwater contamination. The potential risk of contamination of water sources from sewage sludge disposal (along with other routes of transmission) is well recognised and subject to World Health Organization (WHO) guidelines (WHO, 1989; Mara and Cairncross, 1989).

In countries with limited supplies of fresh water, wastewater is used for crop irrigation, either by spray irrigation, overland flow or subsurface infiltration. Wastewater irrigation is also subject to WHO guidelines (WHO, 1989). WHO guidelines for wastewater and excreta use in agriculture are currently undergoing revision.

Many farmers have cellars, tanks or landfills to store manure. Water leaching from these storage sites may contaminate groundwater, especially during periods of rainfall. Storage does reduce the concentration of bacterial pathogens, but (oo)cysts of Cryptosporidium sp. and Giardia sp. can survive for months in manure (Robertson et al., 1992). The application of animal manure to agricultural lands as fertiliser is common practice throughout the world. Application may be by droppings of animals grazing the land, by spraying a manure slurry over the land or by ploughing or injecting manure into the top
layers of the soil. The zoonotic microorganisms present in the manure may leach into the groundwater.

**Figure 4.1. Pathogen transport in an unconfined aquifer**

(From Keswick and Gerba 1980)

![Pathogen transport in an unconfined aquifer](image)

The potential for pathogens from human and animal wastes that are present in the vicinity of wells to contaminate drinking water need special attention. The well construction itself may promote faecal contamination of the aquifer. As the well punctures all layers in the soil above the aquifer, animal droppings or human wastes that are deposited close to the well may travel with percolating rain water directly into the well if the wellhead is not properly protected. Or they may travel along the well wall or in the material surrounding the well in the drill-hole.

### 4.3 Transport and survival

For most faecal pathogens, water is a transmission vehicle rather than a source of pathogens. Most of the enteric pathogens that are discharged into the environment are not able to multiply and need to survive until they are ingested by a suitable human or animal host. This is especially true for obligate parasites, such as the enteric viruses and protozoa like *Cryptosporidium* sp. and *Giardia*
sp. but, in general, this also applies to enteric bacteria: *Campylobacter* spp., *Shigella* spp., *Salmonella* spp., enteropathogenic *E. coli*. There is some evidence that *E. coli* can grow in pristine water in tropical rain forests (Rivera *et al.*, 1988), but it is not clear whether this may also be true for enteropathogenic *E. coli*.

### 4.3.1 Survival in surface water

The ability of pathogens to survive in surface water differs (Ref – pathogens in surface water – in preparation). In general, survival is prolonged when water temperature is low. Other factors that influence survival include sunlight intensity and the presence of aquatic microorganisms that may use the pathogens as a food source or produce exo-enzymes that cause pathogen disintegration. Adsorption to particles facilitates survival, for example LaBelle and Gerba (1980) found that the survival of poliovirus 1, which was adsorbed to sediment, increased four-fold in an unpolluted zone and 96-fold in a polluted zone. Table 4.3 outlines the disappearance rate and time for a 50% reduction in concentration of a number of pathogens in surface water, using examples of published data.

Another factor that affects survival of both faecal index/indicator parameters and pathogens in surface water is the ability of many bacteria to enter the viable but non-culturable (VBNC) stage of growth (Colwell and Grimes, 2000). Briefly, when stressed by a physical or chemical factor (*e.g.* loss of nutrients, adverse temperature, chlorine), many of the bacteria examined thus far respond to the stress by undergoing a series of structural and physiological changes that result in a dormant or ‘non-culturable’ stage of growth. They tend to become smaller, less permeable, refractory to cultivation on culture media normally supportive of their vegetative growth, and some lose their flagella.
Table 4.3. Disappearance rates and reduction times for selected microorganisms in surface water

<table>
<thead>
<tr>
<th>Microorganism</th>
<th>Disappearance rate (per day)</th>
<th>Time for 50% reduction of concentration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pathogens</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parasites</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cryptosporidium sp.</td>
<td>0.0057 - 0.046</td>
<td>15 - 150</td>
</tr>
<tr>
<td>Giardia sp.</td>
<td>0.023 - 0.23</td>
<td>3 - 30</td>
</tr>
<tr>
<td>Viruses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enteroviruses</td>
<td>0.01 - 0.2</td>
<td>3 - 70</td>
</tr>
<tr>
<td>Hepatitis A</td>
<td>0.05 - 0.2</td>
<td>3 - 14</td>
</tr>
<tr>
<td>Rotavirus</td>
<td>0.24 - 0.48</td>
<td>1.2 - 2.4</td>
</tr>
<tr>
<td>Bacteria</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salmonella spp.</td>
<td>1 - 7</td>
<td>0.1 - 0.67</td>
</tr>
<tr>
<td>Shigella spp.</td>
<td>0.7</td>
<td>1</td>
</tr>
<tr>
<td><strong>Vibrio cholerae</strong></td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td><strong>Index parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E.coli</td>
<td>0.23 - 0.46</td>
<td>1.5 - 3</td>
</tr>
<tr>
<td>Coliforms</td>
<td>0.77</td>
<td>0.9</td>
</tr>
<tr>
<td>Enterococci</td>
<td>0.17 - 0.77</td>
<td>0.9 - 4</td>
</tr>
<tr>
<td>F-RNA phages</td>
<td>0.01 - 0.08</td>
<td>29 - 230</td>
</tr>
<tr>
<td>Somatic coliphages</td>
<td>0.6 - 6</td>
<td>2 - 20</td>
</tr>
<tr>
<td>Clostridium perfringens</td>
<td>0.0023 - 0.011</td>
<td>60 - &gt;300</td>
</tr>
</tbody>
</table>

*Vibrio cholerae is environmentally competent and in unfavourable environmental conditions is thought to survive for long periods in water in a non-culturable state (Colwell and Grimes, 2000). Source: DeReignier et al., 1989; Geldreich, 1996; Olson, 1996; Medema et al., 1997; Schijven and Hassanisadeh 2000.

4.3.2 Transport in surface water

Most enteric pathogens have no means of transport (such as motility) in the aquatic environment other than being transported with the water flow. The pathogens can, therefore, be regarded as biological particles that are transported by advection. Many pathogens readily attach to particles in water (Gerba, 1984; Gerba et al., 1978; Wellings et al., 1974) and these particles largely determine the transport characteristics. Sedimentation of planktonic bacteria, viruses and parasites is very slow and probably not significant in determining transport behaviour, but when attached to particles, sedimentation becomes significant.
Sediments may harbour significant numbers of faecal microorganisms. In bottom sediments from bathing beaches, rivers and streams, van Donsel and Geldreich (1971) found thermotolerant coliforms in concentrations that were 100-1 000 fold higher than those in the overlying waters, and viruses levels in sediments are generally 10-fold higher in sediments than in overlying waters. LaLiberte and Grimes (1982) demonstrated extended survival of E. coli inoculated into sediment contained in dialysis bags and placed in a freshwater lake. Re-suspension of sediments, therefore, may give rise to high concentrations of faecal pathogens in water. Rainstorms give rise to re-suspension, as do activities like dredging or shipping (dredge fishing), but the effect of these latter activities appears to be local (Grimes, 1980, 1982).

In temperate lakes thermal stratification may occur during summer and winter. This reduces the exchange of water between the upper and lower layers of lake water. In summer, the quality of the water at the bottom slowly deteriorates due to settling. When de-stratification occurs in the autumn, the water from upper and lower layers mix. This process causes settled particles with coliforms to re-enter the water. In one lake, for example, Geldreich et al. (1989) reported that the autumn destratification led to a 10-fold increase in the coliform densities for several weeks; from a level consistently below 10/100 ml in the summer to more than 100/100 ml.

Rainstorms not only result in water quality deterioration through run-off, stormwater discharges and so on, but they also increase water flows. This may result in more rapid transport of faecal pathogens from the contamination source to abstraction sites. Under normal flow conditions, ‘self-purification’ of water occurs by sedimentation, dilution, sunlight inactivation, predation and starvation. But under rapid flow conditions, self-purification becomes much less significant. In lakes and reservoirs, thermal stratification may strongly reduce the residence time of stormwater. An example of this is provided by Lake Burragorang, a reservoir in Australia. This lake has a length of 40 kilometres and, under normal flow conditions, faecal contaminants are removed through self-purification. The counts of faecal index bacteria and Cryptosporidium sp. at the dam-intake are low. A two-year drought reduced the water level of the catchment reservoirs to 60% of their maximum capacity. The area experienced heavy rains in August 1998. These rains flushed the lands and urban areas leading to stormwater discharges. Some tertiary sewage treatment systems were also flooded by the rapidly rising river water. This contaminated flow entered Lake Burragorang. The lake was stratified, with warm water at the top and the colder contaminated water sank to the bottom of the lake and the flow rapidly reached the dam. Turbidity, temperature and Cryptosporidium sp. data at the dam-intake showed that there was an interchange at the intake of good quality
water from the top layers of the reservoir and poor quality water from the bottom layers within periods of a few days (Deere et al., 2000).

### 4.3.3 Survival in groundwater

Survival of microorganisms is an important feature for groundwater systems (REF – ground water book). The mechanisms of elimination of pathogens by soil passage are adsorption and inactivation. The inactivation rate is influenced by many factors as illustrated in Table 4.4.

**Table 4.4. Factors that influence the survival of microorganisms in soils and thus affect their ability to reach groundwater systems**

(Adapted from Gerba and Bitton, 1984)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Long survival at low temperatures, rapid die-off at high temperatures. For some faecally-derived bacteria high temperatures might give rise to growth.</td>
</tr>
<tr>
<td>Moisture content</td>
<td>Desiccation is detrimental to most microorganisms (spores excepted). An increased rate of reduction will occur in drying soils. This is of most relevance in the unsaturated zone.</td>
</tr>
<tr>
<td>Sunlight</td>
<td>More rapid die-off at the soil surface due to UV irradiation.</td>
</tr>
<tr>
<td>pH</td>
<td>Bacteria die-off more rapidly in acid soils (pH 3-5) than in alkaline soils. The pH influences the adsorption of microorganisms to the soil matrix and indirectly influences survival.</td>
</tr>
<tr>
<td>Microflora</td>
<td>Soil bacteria and fungi may produce exo-enzymes that damage the structure of faecal microorganisms, while amoebae and other microbiota may feed on them. Bacterial survival is shorter in natural soils than in sterilised soils, but for viruses no clear trend is observed.</td>
</tr>
<tr>
<td>Organic carbon content</td>
<td>The presence of organic carbon increases survival and may give rise to the regrowth of bacteria.</td>
</tr>
<tr>
<td>Cations</td>
<td>Certain cations have a thermal stabilising effect on viruses and increase virus survival. Cations also enhance virus adsorption to soil and this indirectly increases survival, as viruses appear to survive better in the adsorbed state.</td>
</tr>
</tbody>
</table>

Pathogen survival in groundwater has been determined in a number of ways, including:
• Suspending laboratory microorganisms in microcosms.
• Sterile groundwater in flasks in the laboratory or under ambient conditions.
• Membrane chambers in flowing groundwater.
• Dialysis tube in groundwater wells.

The disappearance rates in groundwater are lower than in surface water (see Table 4.5). Viruses survive longer than bacteria. No data on the survival of protozoan parasites in groundwater are available yet, but it can be assumed that these pathogens are able to survive longer than the viruses.

**Table 4.5. Example disappearance rates of enteric microorganisms in natural groundwater**

<table>
<thead>
<tr>
<th>Microorganism</th>
<th>Disappearance rate (per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Viruses</strong></td>
<td></td>
</tr>
<tr>
<td>Hepatitis A virus</td>
<td>0.10 - 0.33</td>
</tr>
<tr>
<td>Poliovirus 1</td>
<td>0.013 - 0.77</td>
</tr>
<tr>
<td>Coxsackievirus</td>
<td>0.19</td>
</tr>
<tr>
<td>Rotavirus SA11</td>
<td>0.36</td>
</tr>
<tr>
<td>Coliphage T7</td>
<td>0.15</td>
</tr>
<tr>
<td>Coliphage f2</td>
<td>0.39 - 1.42</td>
</tr>
<tr>
<td>MS2</td>
<td>0.063 - 0.75</td>
</tr>
<tr>
<td><strong>Bacteria</strong></td>
<td></td>
</tr>
<tr>
<td><em>Escherichia coli</em></td>
<td>0.063 - 0.36</td>
</tr>
<tr>
<td>Faecal streptococci</td>
<td>0.03 - 0.24</td>
</tr>
<tr>
<td><em>Salmonella typhimurium</em></td>
<td>0.13 - 0.22</td>
</tr>
<tr>
<td><em>Clostridium bifermantans</em> spores</td>
<td>0.00</td>
</tr>
</tbody>
</table>


### 4.3.4 Groundwater transport

The most important factors in the transport of microorganisms through the subsurface are water flow (the driving force) and soil texture. Most of the studies on groundwater transport have focussed on viruses. The transport of viruses through soil is primarily determined by attachment (Schijven and Hassanisadeh, 2000), while virus inactivation is considered to be less/insignificant (Bales *et al.*, 1995, 1997; Pieper *et al.*, 1997; DeBorde *et al.*, 1998, 1999). Many factors affect the adsorption and transport of
microorganisms through soil (Table 4.6). The major factor that affects virus adsorption is pH (Schijven and Hassanisadeh, 2000). At higher pH, electrostatic repulsion increases, resulting in a decreased attachment rate and an increased detachment rate. In most aquifers, surface characteristics of the soil are heterogeneous and also viruses with different isoelectric points may be present. Therefore, dependent on pH and thus on the charge of the virus and soil particles, adsorption of some of these viruses may be irreversible, whereas that of others may be reversible. At pH 7 – 8, adsorption will be mainly reversible.

**Table 4.6. Factors affecting transport of enteric pathogens through soil**

(Adapted from Gerba and Bitton, 1984; Schijven and Hassanisadeh, 2000)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Influence on transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil texture</td>
<td>Fine-textured soils retain viruses, bacteria and protozoa more effectively due to increased interaction and adsorption. Fractured soils, however, are poor retainers of microorganisms.</td>
</tr>
<tr>
<td>Water flow</td>
<td>Water flow is the driving force of transport and pathogen transport velocities appear to be proportional to the water flow. Increased water flow may remobilize adsorbed microorganisms.</td>
</tr>
<tr>
<td>PH</td>
<td>Adsorption generally increases when pH decreases, due to reduced electrostatic repulsion.</td>
</tr>
<tr>
<td>Cations</td>
<td>The presence of multivalent cations (Ca$^{2+}$, Mg$^{2+}$) increases adsorption due to the formation of salt bridges between negatively charged microorganisms and soil particles.</td>
</tr>
<tr>
<td>Metal hydroxides</td>
<td>Iron hydroxides improve the adsorption of microorganisms.</td>
</tr>
<tr>
<td>Soluble organics</td>
<td>These can influence transport in various ways: they may compete with microorganisms for attachment sites (humic and fulvic acids compete with viruses), but they may also give rise to microbial activity that enhances attachment and inactivation.</td>
</tr>
<tr>
<td>Microorganism</td>
<td>Bacteria and parasites are more readily removed than viruses because of their size (1 - 20 µm versus 20 - 80 nm). Differences in isoelectric points and surface composition determine the adsorption rates.</td>
</tr>
<tr>
<td>characteristics</td>
<td></td>
</tr>
<tr>
<td>Saturated versus</td>
<td>Under unsaturated flow conditions, water fills only the small pores. This increases soil-microorganism contact and adsorption.</td>
</tr>
<tr>
<td>unsaturated flow</td>
<td></td>
</tr>
</tbody>
</table>
4.4 Catchment surveys and catchment protection

As indicated earlier, catchment protection is an essential step in safeguarding the microbial quality of drinking water. The basic concept of catchment protection is to know the catchment hydrology/hydrogeology and sources of pathogen contamination in the catchment in order to:

- Select the most appropriate site for drinking water abstraction or well placement.
- Be able to select appropriate catchment monitoring and/or protection measures.
- Predict the occurrence of peak events.

A sanitary survey of the catchment area can identify sources of faecal contamination (sewage treatment plants, sewer overflows, agricultural areas with manure storage or land deposition, high waterfowl numbers etc.). It can also identify if certain climatological (heavy rainfall), environmental (high animal loads) or man-made conditions (agricultural practices, tourism) are likely to give rise to peak contamination events of the source water.

A survey of sources can be done without the use of index parameters by mapping the catchment and the sources of faecal contamination present. This is the basic hazard assessment step in the catchment. In a second stage, a survey can be conducted with the well-established microbial indices of faecal pollution (E. coli, enterococci, spores of Clostridium perfringens), non-microbial water quality data (e.g. turbidity, temperature, pH, conductivity) and hydrologic data (measurements of flow and precipitation). This will provide more accurate and quantitative information about the quality of the waters in the catchment areas and the effect of transport on the level of faecal pollution. If the methods and resources are available, the inclusion of F-RNA bacteriophages in such a survey is likely to improve its prediction with regard to virus hazards.

Other, non-microbial parameters have been suggested as indicators of contamination with domestic wastewater. These are compounds that are used in the household such as boron (used as whitener in washing powders) and caffeine, and other human excretory products such as secretory IgA, sterols and urobilin. None of these, has been demonstrated to be widely applicable, but may be useful for specific purposes.
4.4.1 Surface water

4.4.1.1 Catchment survey

For surface water systems, this inventory should include:

- Location and size of discharges of treated sewage.
- Location and size of discharges of untreated sewage.
- Location and size of sewer overflows and conditions initiating overflow.
- Location of sewage sludge deposits and ability of contaminants to enter surface water.
- Location, type, frequency, conditions and size/weight of manure application on land in agricultural areas.
- Location and type of manure deposits and ability of contaminants to travel to surface water.
- Presence of high numbers of wild mammals and birds on or around the surface water.

For all these aspects, special attention should be given to circumstances that may lead to peak contamination events. A simple classification relating to the estimated significance of the pollution source is helpful and can be based on its nature, size, the transport time and its distance from the source water.

The catchment survey should result in:

- An inventory of the contamination sources.
- A classification of their significance.
- An inventory of conditions that may give rise to peak contamination events.

During the survey possible risk management measures may be identified and, after the survey is completed, it is generally possible to classify catchment protection measures according to their (estimated) impact on the improvement of the source water quality or prevention of peak events.

A basic catchment survey is not sophisticated (although geographical information system (GIS) techniques are helpful). Despite this, however, they are not very well established within the water community. There are some examples of catchment surveys, such as those in several German reservoir
catchments (Feuerpfeil and Bischoff, 2001), but in general, emphasis has more commonly been placed on treatment. This may be because treatment is totally within the control of the water supplier, while catchment protection may involve many different bodies and interest groups and is, therefore, more difficult to manage. However, the recognition of Cryptosporidium sp. as an important waterborne pathogen and its resistance to disinfection has boosted interest in catchment protection, especially in North America. Following an incident in Australia in 1998, where water in distribution was found to be contaminated with Cryptosporidium (probably as a result of high levels within the catchment following heavy rainfall - McLellan, 1998) a Catchment Authority was set up, with their first step being to make an inventory of contamination sources (Deere et al., 2000).

4.4.1.2 The use of microbial parameters as an index of faecal pollution

An initial catchment survey focussing on the identification of sources can be conducted without the use of microbial indices, however, such measurements may help to determine the significance of any identified pollution sources and also the behaviour and transport of faecal contamination in surface water. They are especially helpful in assessing the occurrence of peak events and may even be used to predict these. The principal microorganism for this purpose is E. coli, as it is present in all faecal contamination of concern and the assay is inexpensive, simple and widely used. Its presence in surface water indicates recent faecal contamination and therefore a potential health hazard. Thermotolerant coliforms can be a suitable alternative, but where these are used attention must be given to the possible presence of waste effluents with a high carbohydrate content, as they may harbour Klebsiella sp.

As E. coli is not as environmentally long-lived as many pathogens (i.e. viruses and protozoa) it is most useful in identifying recent contamination. Additional, complementary tests examining for the more robust enterococci and the spores of Clostridium perfringens can shed light on less recent faecal contamination.

Due to high thermophilic background growth on the culture media and the potential multiplication of thermotolerant coliforms (and even E. coli) in the environment (Rivera et al., 1988; Byappanahalli and Fujioka, 1998), the use of some microbial parameters to assess tropical source water quality is problematic. Clostridium perfringens spores appear to be the most appropriate parameter for assessing faecal contamination in tropical climates (Fujioka, 2001).
Case study: Using monitoring within a water safety plan to prevent contamination

One of the catchments within the Melbourne Water area in Australia is a protected natural mountain area with no human settlements. The water is held in reservoirs and is only chlorinated before distribution to the consumers. Catchment surveys and monitoring showed that rainfall led to deterioration in the water quality in the tributaries to the reservoir with both relatively high turbidity and concentrations of faecally derived bacteria. To attempt to remedy this, a standard operating procedure was set up, using flow diversion as a control measure to prevent water of relatively poor quality entering the reservoir (Deere et al., 2000).

4.4.1.3 The use of pathogenic microorganisms

It is generally considered that surveys assessing pathogenic microorganisms give the most direct information about their sources. There are, however, many different pathogens, they are present in relatively low concentrations and require large sample volumes and pathogen detection methods (if available) are generally high-tech, time-consuming and expensive. Thus pathogen surveys rarely allow large numbers of samples to be taken. Such surveys are, therefore, best preceded by catchment surveys, sanitary inspection and faecal index investigation and then targeted to specific research questions, as illustrated by the following case study.

Case study: First flush

In the California State Water project in the USA, several lakes are used as source waters. Two of these lakes are Castaic Lake in the Castaic Mountains and Silverwood Lake in the San Bernardino National Forest. No agricultural, industrial or sewage discharges were identified in the streams sampled during sanitary surveys, but livestock and wildlife were present in the vicinity of the creeks. For the Cryptosporidium and Giardia monitoring programme, sampling sites were selected in the lakes and in tributaries and three sampling strategies were used:

- Large volume (100 l) sampling with filters.
- Unattended stormwater grab samplers (5 l).
- 4 l grab samples for storm events other than first flush.
The first flush during storm events contained very high numbers of *Cryptosporidium* sp. and *Giardia* sp. (Table 4.7). These high concentrations go unnoticed in the filter sampling that was not driven by precipitation but also the grab samples during storm events did not detect these high numbers (Stewart *et al.*, 1997).

**Table 4.7. Results of the Castaic and Silverwood lake surveys with different monitoring strategies**

<table>
<thead>
<tr>
<th>Sampling strategy</th>
<th>Cryptosporidium sp.</th>
<th>Giardia sp.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% positive</td>
<td>Range (no/100 l)</td>
</tr>
<tr>
<td>Filter</td>
<td>10</td>
<td>3 - 415</td>
</tr>
<tr>
<td>First flush</td>
<td>35</td>
<td>46 - 41 666</td>
</tr>
<tr>
<td>Grab sampling</td>
<td>19</td>
<td>3.4 - 647</td>
</tr>
</tbody>
</table>

Hence, the first flush during storm events carry the highest load of *Cryptosporidium* and *Giardia* to the streams and should be included in monitoring programmes or somehow accounted for. The first flush samplers were inexpensive, but were vulnerable to theft and vandalism.

### 4.4.2 Groundwater

#### 4.4.2.1 Catchment survey

As outlined earlier, primary sources of groundwater contamination are human and animal wastes and the infiltration of faecally contaminated surface water (including rivers). As groundwater treatment generally does not include major barriers against pathogens, groundwater catchment protection acts as the principal barrier. However, it should not necessarily be assumed that groundwater does not require filtration to remove protozoa (*e.g.* where the filtration provided by the ground between a river and a well is inadequate to remove protozoa) or disinfection to inactivate viruses.

The catchment survey needs to collect information about the sources of contamination in the catchment, the hydrogeology of the groundwater system and the high risk factors such as the possibility of rapid pathogen transport through pores/fractures or contamination of wells, drains or adits from nearby sources.
Geohydrological survey

This should include investigation of the following:

- Catchment area (if no detailed information is available, an estimation based on abstraction rate and thickness and porosity of the aquifer is appropriate).
- Soil layer texture and composition; the presence, thickness and integrity of confining soil layers.
- Flow lines of water to the abstraction sites in different layers.
- Presence of solutions, thin unsaturated zones, surface-water aquifer contact.

Survey of the sources of contamination and high risk factors

Sources of contamination could include, sites for disposal of sewage, treated sewage or sewage sludge, sites for disposal or land application of manure, areas with irrigation with treated or untreated domestic wastewater, septic tanks, cesspools, latrines, waste dumps, manure storage facilities and so on (see also REF groundwater book).

High risk factors are those that result in the rapid transport of water to the groundwater source, such as heavy rainfall or infiltration of river water.

Well-head, well, borehole protection and protection of shallow aquifers and drains

The aspect should include an assessment of sources of contamination in the vicinity of the wells (grazing animals, septic systems, sewers and so on), the well-head integrity and the integrity of the soil around the well (placement and integrity of well sheets, clay layer or concrete slabs around the well). An example inspection form from the WHO is shown in Figure 4.2 and Box 4.1 (WHO, 1997). For shallow aquifers and drains, areas of surface-aquifer contact or small unsaturated zones (especially during rainfall) should be examined, as should the integrity of ventilation shafts and manholes, and also the procedures for opening and entering manholes.
Box 4.1. Example survey form for tubewell with hand-pump

WHO, 1997

I Type of facility TUBEWELL WITH HAND-PUMP
1. General information: Health centre ..........................................................
   Village ..........................................................
2. Code no.—Address ..............................................................................
3. Water authority/community representative signature ............................
4. Date of visit ..........................................................
5. Water sample taken? Yes Sample no. Thermotolerant coliform grade 

II Specific diagnostic information for assessment
   Risk
1. Is there a latrine within 10 m of the hand-pump? Y/N
2. Is the nearest latrine on higher ground than the hand-pump? Y/N
3. Is there any other source of pollution (e.g., animal excreta, rubbish, 
   surface water) within 10 m of the hand-pump? Y/N
4. Is the drainage poor, causing stagnant water within 2 m of the 
   hand-pump? Y/N
5. Is the hand-pump drainage channel faulty? Is it broken, permitting 
   ponding? Does it need cleaning? Y/N
6. Is the fencing around the hand-pump adequate, allowing animals in? Y/N
7. Is the concrete floor less than 1 m wide all around the hand-pump? Y/N
8. Is there any ponding on the concrete floor around the hand-pump? Y/N
9. Are there any cracks in the concrete floor around the hand-pump which 
   could permit water to enter the well? Y/N
10. Is the hand-pump loose at the point of attachment to the base so that 
    water could enter the casing? Y/N

Total score of risks ................... /10

Contamination risk score: 9–10 = very high; 6–8 = high; 3–5 = intermediate; 
0–2 = low

III Results and recommendations
The following important points of risk were noted: ............................... (list nos 1–10) 
and the authority advised on remedial action.

Signature of sanitarian ..................................................
Figure 4.2. Diagram to accompany example inspection form (Box 4.1) for tubewell with hand-pump

(WHO, 1997)

MSD: minimum safe distance determined locally.
1-10 refer to the survey form (Section II) – Box 4.1.

In some countries, inventories of sources of groundwater contamination (both for microbial and chemical contaminants) are better established than in surface water systems. In these countries, groundwater protection regulation has been issued that relies on the division of the catchment area into zones of different vulnerability to contamination. The zones are defined by (average) transit time of the water from the land surface to the source water. Activities that may lead to groundwater contamination are restricted in these protection zones.
Case study: Recommendations from the UK Group of Experts

An outbreak of cryptosporidiosis in North London (UK) was subsequently traced to a groundwater supply that was vulnerable to infiltration of surface water containing Cryptosporidium sp. (DWI, 1998). This and several other incidents with groundwater supplies triggered the UK Group of Experts to recommend that groundwater systems should be evaluated for potential contamination risk (Bouchier, 1998). The groundwater protection practice at the time was based (as in many countries) on land surface zoning according to travel times of the water from the land surface to the groundwater sources and the restriction of contaminating activities in the most vulnerable zones. Bouchier (1998) evaluated these practices for their protective value against microbial pollution, especially with Cryptosporidium sp. It was concluded that this approach formed a sound basis for assessing vulnerable groundwater supplies, but also that there were some limitations. An important limitation is that by-pass features, which allow rapid transport of water with contaminants to groundwater, were not incorporated in the vulnerability assessment. By-pass flow may occur in many of the British carbonate aquifers. Similarly, surface water-aquifer interactions that may occur in valley-bottoms (surface water recharge) and upper catchments were not incorporated in the vulnerability assessment. Bouchier (1998) recommended the inclusion of an additional vulnerability class in the zoning scheme. This extreme vulnerability class would apply to areas with the combination of contaminated surface water and rapid access points (solution features, sinkholes, karst or pseudo karst features, mines and aggregate extraction sites).

The need for the inclusion of rapid access of surface water to groundwater as an important factor in vulnerability assessment was illustrated by the fact that eight of the nine suspected cases of groundwater contamination with Cryptosporidium sp. in the UK were associated with adited wells, collectors, spring galleries and former mines with adits (Morris and Foster, 2000). Groundwater supplies in rural settings were more commonly affected than sites in urban settings. Fissure flow, dual porosity flow and intergranular flow were all represented in these cases. Intergranular flow appeared only to be important in settings where the residence time in the aquifer was very short, such as in river gravels close to a surface water course.

The Expert Group listed the factors of a groundwater system that need to be considered for assessing the risk of contamination with Cryptosporidium sp. (Table 4.8) and gave guidance on techniques to determine/verify the significance of these factors. Simple qualitative ranking may help to prioritise the different hazards, however, Morris and Foster (2000) stress the need to focus on the individual water supply when applying ranking, appreciating the
unique hydro-geological, operational and contamination sources setting of each supply system.

Table 4.8. Factors for consideration in the risk assessment of groundwater contamination
(From Bouchier, 1998)

<table>
<thead>
<tr>
<th>Predisposing groundwater to Cryptosporidium sp. risk</th>
<th>Possible verification techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Catchment factors</strong></td>
<td></td>
</tr>
<tr>
<td>High wastewater returns, including sewage effluent to river reaches, especially under baseflow conditions</td>
<td>Hydrochemistry, microbiology, hydrometry</td>
</tr>
<tr>
<td>Livestock rearing in inner catchment, especially if intensive</td>
<td>Farm survey</td>
</tr>
<tr>
<td>Likely Cryptosporidium sp. - generating activities in catchment – e.g. abattoirs</td>
<td>Economic activity survey</td>
</tr>
<tr>
<td>Urbanising catchment</td>
<td>Land registry survey</td>
</tr>
<tr>
<td>Livestock grazed or housed near wellhead</td>
<td>Site inspection</td>
</tr>
<tr>
<td><strong>Hydrogeological factors</strong></td>
<td></td>
</tr>
<tr>
<td>Known or suspected river aquifer connection nearby</td>
<td></td>
</tr>
<tr>
<td>Unconfined conditions with shallow water table</td>
<td></td>
</tr>
<tr>
<td>Karst or known rapid macro-fissure flow conditions, especially in shallow groundwater</td>
<td></td>
</tr>
<tr>
<td>Patchy drift cover associated with highly contrasting aquifer intrinsic vulnerabilities</td>
<td></td>
</tr>
<tr>
<td>Solution features observed or inferred in catchment</td>
<td></td>
</tr>
<tr>
<td>Shallow flow cycles to springs</td>
<td></td>
</tr>
<tr>
<td>Fissure-dominant flow (as suggested by high transmissivity or specific capacity)</td>
<td></td>
</tr>
<tr>
<td><strong>Well/raw water source factors</strong></td>
<td></td>
</tr>
<tr>
<td>Supply source tapping shallow flow systems (e.g. adits, springs, mine galleries)</td>
<td>Check site plans, tracing</td>
</tr>
<tr>
<td>Adits with upbores or construction-stage ventilation shafts</td>
<td>Check site plans, site inspection</td>
</tr>
<tr>
<td>Poor casing integrity</td>
<td>CCTV, geophysical logging</td>
</tr>
<tr>
<td>Masonry linings above pumping water level without additional sanitary seal</td>
<td>CCTV, check site plans</td>
</tr>
<tr>
<td>Sewer/septic tank/slurry pit systems near wellhead or above adits</td>
<td>Site inspection</td>
</tr>
<tr>
<td>Inadequately fenced source especially around spring boxes, catchpits, galleries</td>
<td>Site inspection</td>
</tr>
<tr>
<td>Old, poorly documented well construction</td>
<td>Site plans/BGS national well record archive</td>
</tr>
</tbody>
</table>

4.4.2.2 The use of microbial indicators as an index of faecal pollution

Groundwater is not easily accessible for monitoring faecal contamination. Sources of faecal contamination that have been identified in the sanitary survey can be monitored and may give quantitative information on the size of the sources but not necessarily on their impact on groundwater quality.

The subsurface catchment can be monitored for faecal contamination with observation wells, if the hydro-geology has been well established. This is especially true for karst or fractured bedrock aquifers, because the water flow is difficult to establish. The ideal placement of observation wells is between the sources of contamination and the abstraction wells. Detailed guidance on sampling of groundwater and well drilling and placement can be found in McNabb and Mallard (1984). Monitoring of the observation wells for index parameters can give information about the efficiency of soil passage. Microbial parameters that can give information about the presence of faecal contamination are *E. coli*, bacteriophages and spores of *Clostridium perfringens*. The application of these parameters in observation wells is similar to source water monitoring for groundwater systems. Important recommendations are:

- Sample volumes should be as large as achievable (Fujioka and Yoneyama, 2001 recommend analysis of 1 000 ml samples).
- Sampling strategy should include regular sampling and high risk event sampling. In this respect, observation wells should be placed in the flow lines from high risk areas to source water and preferably leave sufficient residence time to take appropriate actions (e.g. shut-down of wells).
- When resources/available methods are limited, use *E. coli* testing. When resources are available include testing for enterococci, spores of *Clostridium perfringens* and F-specific RNA phages if sewage or other human wastes are thought to be important pollution sources.

Case study: The importance of large volumes

To increase production capacity, Water Company Limburg (in the Netherlands) has constructed additional wells along the banks of the River Meuse. Hydrological calculations indicated that 10-15% of the abstracted water is bank filtrate. The aquifer consists of coarse and fine gravel with sand and the average residence time of the river water in the soil is 0.5–3 years. One of the wells close to the river (150 m) extracts 50% river water and the estimated residence time to this well is 45-65 days. Due to the nature of the Meuse (rain-fed river), sudden sharp rises in the river level occur that can lead to infiltration
of previously unsaturated soil layers with high velocities and short residence
times. To determine the relationship between the residence time (or distance of
soil passage through the aquifer) and the removal of pathogenic
microorganisms, large volume samples (up to 100 l) were taken from the river
and from two observation wells located between the river and the pumping well
closest to the river. The samples were analysed for the presence of
thermotolerant coliforms, spores of sulphite reducing clostridia,
Cryptosporidium sp., Giardia sp., entero- and reoviruses, somatic coliphages
and F-specific RNA phages. All were present in the River Meuse throughout the
study period. In the observation well at a distance of 8 m from the river,
thermotolerant coliforms, spores of sulphite-reducing clostridia, bacteriophages
and reoviruses were detected (Figure 4.3). No enteroviruses were found.
Cryptosporidium and Giardia were tested once and not detected. In the
observation well further from the river only thermotolerant coliforms, spores
and bacteriophages were detected. In the pumping well, thermotolerant
coliforms, spores of sulphite-reducing clostridia and somatic coliphages were
occasionally detected. The highest concentrations in the well were observed
after the water level in the River Meuse had been high and the distance and
travel time to the observation well was relatively short.

The first metres of soil passage resulted in relatively efficient removal,
probably because this includes passage through the relatively impermeable layer
of river sediment on the bank. Strict hygiene measures were necessary to
prevent contamination of the observation wells from the soil surface. The
occasional presence of several indices of faecal pollution in the well indicated
that microorganisms (including pathogens) from the river may pass through the
soil into the well, especially during high river flows. The results were used to
design an abstraction programme in which the well(s) close to the river are shut
down in case of a sharp rise in river flow (Medema et al., 2000b).
4.5 Source water quality

For source water quality assessment, the different nature of the sources means that a clear distinction between surface water and groundwater sources is necessary. For surface water, assessment of the microbiological quality of the source water is essential in both the design and the operation phase of drinking water treatment:

- To design an appropriate treatment system that transforms the source water into safe drinking water.
- To evaluate if an existing treatment system is able to provide safe drinking water.
- To target the treatment to cope with variations and peak events in the faecal contamination of source water.

In most groundwater systems, faecal contamination is generally low or even absent. If the groundwater is influenced by surface water then the monitoring programme should also include the surface water (this can be
targeted to conditions or times when surface water influence is likely). For the most part, monitoring is used to verify the purity of the groundwater, rather than to determine treatment goals, however, if the groundwater is influenced by faecal contamination, then monitoring has both functions \(i.e\). verification of the efficacy of the soil passage, and assessment of the additional treatment level required).

The first stage of the assessment of source water quality is monitoring for the traditional microbial indices of faecal pollution, possibly supplemented with bacteriophages. This monitoring programme should be frequent in order to identify short-term variations in water quality. If certain climatological, natural conditions or human practices lead to an increase in the faecal contamination of the source water, monitoring intensity (frequency and potentially the number of parameters) should be increased during the period when these conditions occur. Monitoring for pathogens is (as for catchment surveys) secondary to index monitoring and should only be considered when there is a strong suspicion of contamination. Although it should be noted that pathogen monitoring can provide useful information. In source water, for example, quantitative information on pathogen occurrence provides data that can be helpful in setting treatment goals. In groundwater supplies it can be useful as a way to determine the ability of pathogens to travel through the soil. However, when only low levels of index parameters are detected, the probability of finding pathogenic microorganisms decreases.

4.5.1 Surface water

4.5.1.1 The use of microbial parameters to set treatment goals

Microbial parameters can be used to determine the level of faecal contamination at a specific surface water site. The more contaminated a surface water source, the more treatment is necessary to produce safe drinking water. This is the basis of microbial guidelines for raw water quality, such as those in the EC directive 75/440/EEC (Table 4.9).
Table 4.9. Thermotolerant coliform standards for surface water intended for the abstraction of drinking water

(EC, 1975)

<table>
<thead>
<tr>
<th>Category</th>
<th>Thermotolerant coliform concentration/100 ml</th>
<th>Treatment requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>20</td>
<td>Simple physical treatment and disinfection</td>
</tr>
<tr>
<td>A2</td>
<td>2,000</td>
<td>Normal physical treatment and disinfection</td>
</tr>
<tr>
<td>A3</td>
<td>20,000</td>
<td>Intensive physical treatment and disinfection</td>
</tr>
<tr>
<td>A4</td>
<td>&gt;20,000</td>
<td>Not suitable for drinking water production</td>
</tr>
</tbody>
</table>

Many studies have looked at the relationship between microbial indices of faecal pollution and pathogens in surface water. Although this has been subject of much debate, the consensus appears to be that there is a general, coarse relationship between the indices of faecal pollution and pathogen concentrations. Basically, sewage contains higher concentrations of both the index parameters and pathogens than treated sewage and this is again higher than in surface water and after reservoir storage. So, based on the microbial index parameter concentration, a rough estimate of pathogen concentrations can be given (Payment et al., 2000). When it comes to predictions of the pathogen concentration at a particular site, however, the correlation found in general (and even at the location itself) is generally too uncertain to be able to predict the pathogen concentration with less than one to two log-units uncertainty margin on either side of the estimate (Havelaar, 1996).

4.5.1.2 The use of pathogens to set treatment goals

LeChevallier and Norton (1995) sampled raw waters supplying 72 drinking water plants in the USA for the occurrence of *Cryptosporidium* sp. and *Giardia* sp. They calculated the required treatment efficiency on the basis of the concentration of parasites in the raw water and the maximum concentrations allowable in drinking water (determined by the $10^{-4}$ risk of infection value used in risk assessment studies in the USA and elsewhere – see Section 1.5.1). Similar studies were conducted in Canada (Payment et al., 2000; Barbeau et al., 2001) and in the Netherlands (Medema et al., 2000c), however, current detection methods make interpretation of such monitoring data for *Cryptosporidium* sp. and *Giardia* sp. difficult. The recovery efficiency of the methods are low and variable and the methods do not discriminate between live and dead (oo)cysts nor do they identify which (oo)cyst types are infective to
humans. The conservative approach is to consider all (oo)cysts to be infective, but this may give rise to higher investments in treatment processes than necessary to protect public health adequately. The recent developments in molecular detection methods may bring the required specificity within reach but will not resolve the problems associated with recovery.

Virus surveys have been conducted for the same purpose. The occurrence of enteroviruses in raw water has been monitored in many countries and levels have been found to range from 0.1-100 /l (Block et al., 1978; Nestor et al., 1981; Payment, 1981; Lucena et al., 1982; van Olphen et al., 1984). While many of the enteric viruses can be cultivated and concentrated from water samples with reasonable efficiency, some of the viruses responsible for waterborne outbreaks cannot be cultivated (e.g. Norwalk, hepatitis E and so on). If the objective is to estimate a general level of viral contamination, current methods provide a fair assessment. In the case of outbreak investigation, molecular methods can be used to supplement current methods by providing tools to identify the aetiological agent (see Chapter 7). A combination of cell culture and molecular methodology is being developed (see Chapter 8) which may provide good data for source waters.

4.5.1.3 Peak events

Precipitation events can lead to a high pathogen load in the source water. Although this is generally true for all faecal pathogens from domestic and agricultural sources, recent research has focussed primarily on Cryptosporidium sp. and Giardia sp. This research can be used to illustrate the significance of peak events and the strategies to monitor for peak events such as storms (Gibson et al., 1998; Stewart et al., 1997). Several authors have found a relationship between rainfall and high concentrations of Cryptosporidium sp. and Giardia sp. (Poulton et al., 1991; Hansen and Ongerth, 1991; Atherholt et al., 1998). The high concentrations were associated with agricultural run-off, re-suspension of river sediments and sewer overflows.

Rainfall also leads to increased water flows and may result in the short-circuiting of pre-treatment reservoirs, as outlined earlier. Flooding, as a result of exceptional rainfall events, can lead to even more extreme contamination. As the floodwater can wash the contents of complete sewage systems, sewage treatment works and sludge disposal stores into surface water and may lead to power failure, mains break and even submersion of drinking water treatment facilities.
Case study: The importance of frequent and/or event-based monitoring

The Delaware River flows through the States of New York, Pennsylvania and New Jersey (USA). 1.2 million people live in the river basin. Sources of faecal pollution include combined storm and domestic wastewater sewers, septic systems, discharges of treated domestic wastewater, water recreation and run-off. The Trenton Water Works collects water from this river for the production of drinking water by flocculation, alum coagulation, sedimentation, rapid sand filtration and chlorine disinfection. The abstracted water was sampled monthly for *Cryptosporidium* sp., *Giardia* sp., indicator bacteria, coliphages and other parameters (i.e. turbidity, particles, suspended solids, temperature, river flow). Additionally, the sampling frequency was increased to daily samples (Monday – Friday) in three consecutive weeks during the winter and this was repeated in spring, summer and autumn. To determine the effect of this difference in sampling strategy, the monthly samples were compared to all data and are summarised in Table 4.10 (Atherholt *et al*., 1998).

**Table 4.10. Comparison of sampling strategies: monthly sampling versus all data**

<table>
<thead>
<tr>
<th></th>
<th><em>Cryptosporidium</em> sp.</th>
<th><em>Giardia</em> sp.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Monthly</td>
<td>All</td>
</tr>
<tr>
<td>Percent detection (%)</td>
<td>92</td>
<td>88</td>
</tr>
<tr>
<td>Geometric mean (n / 100 l)</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td>90-percentile (n / 100 l)</td>
<td>134</td>
<td>160</td>
</tr>
<tr>
<td>Minimum (n / 100 l)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Maximum (n / 100 l)</td>
<td>140</td>
<td>800</td>
</tr>
</tbody>
</table>

While the monthly samples did reflect the central tendency for (oo)cyst occurrence, it underestimated both the 90-percentile and maximum occurrence of the parasites. In addition, LeChevallier and Norton (1995) examined the relationship between *Cryptosporidium* sp., *Giardia* sp. and the other water quality parameters. Although no correlation was found to be consistently present in all time series tested, correlations between protozoa concentrations and turbidity, river flow and thermotolerant coliforms (or *E. coli*) were repeatedly found. The authors developed a simple model for the prediction of peak events based on these indicators of pollution.
Case study: Turbidity and spores of Clostridium perfringens as indices of pollution

The River Meuse is a river fed primarily by rain water, which flows from Northern France, through eastern Belgium and the Netherlands to the North Sea. The river receives discharges of treated and untreated domestic wastewater and flows through agricultural areas with a high density of livestock. The river water is abstracted near Keizersveer for the production of drinking water by reservoir storage (typically five months in a series of three reservoirs) and coagulation/filtration with chlorination or ozonation and granular activated carbon filtration. In 1994, the river water was sampled weekly for indicator bacteria, Cryptosporidium sp. and other parameters such as turbidity and temperature. The Meuse is a typical rain-fed river, with high flows and high turbidities in winter and spring, due to rainfall and melting snow. At this time the level of faecal pollution, as judged by the concentration of index bacteria, is also relatively high and the water temperature is low. Monitoring showed that several, but not all, of the peak concentrations in Cryptosporidium sp. coincided with a peak in turbidity (Figure 4.5, week 3, 4, 5, week 12, week 15, week 44 and week 50) (Medema, 1999). A turbidity peak therefore indicates the potential presence of high Cryptosporidium sp. concentrations (a similar relationship has been observed in the Delaware river (USA), Atherholt et al., 1998).

Figure 4.5. Coincidence of peaks in turbidity measurements with peaks in Cryptosporidium sp. counts in river water

(Medema, 1999)
The concentration of *Cryptosporidium* sp. was positively correlated with flow and turbidity, and with faecal indicator bacteria, especially with clostridial spores (Table 4.11). Spores and oocysts are both very persistent in the aquatic environment, and it may be this feature that is the basis of the correlation.

Table 4.11. Correlation between *Cryptosporidium* sp. concentrations and other water quality parameters in the River Meuse (product-moment correlation coefficients) (Medema, 1999)

<table>
<thead>
<tr>
<th>Water quality parameter</th>
<th>r-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spores of sulphite reducing clostridia</td>
<td>0.75***</td>
</tr>
<tr>
<td>Spores of <em>Clostridium perfringens</em></td>
<td>0.76***</td>
</tr>
<tr>
<td>Total coliforms</td>
<td>0.51**</td>
</tr>
<tr>
<td>Thermotolerant coliforms</td>
<td>0.58***</td>
</tr>
<tr>
<td>Faecal streptococci</td>
<td>0.57***</td>
</tr>
<tr>
<td>Temperature</td>
<td>-0.44</td>
</tr>
<tr>
<td>Chlorophyll A</td>
<td>-0.27</td>
</tr>
<tr>
<td>River flow</td>
<td>0.61***</td>
</tr>
<tr>
<td>Turbidity</td>
<td>0.66***</td>
</tr>
<tr>
<td>NH$_4^+$</td>
<td>0.38</td>
</tr>
</tbody>
</table>

* significant at the 0.05 level.  
** significant at the 0.01 level.  
*** significant at the 0.001 level.

This case study shows that raw water turbidity can be used as an easy and rapid (even on-line) indicator of the presence of *Cryptosporidium* sp. (and probably other pathogens related to faecal contamination). The turbidity measurements serve as a trigger to stop the intake of river water into the reservoirs, while the reservoirs allow the continuation of drinking water production. The study also showed that spores of *Clostridium perfringens* are the best indices of the presence of *Cryptosporidium* sp., probably because both spores and oocysts are robust survival stages.

4.5.2 Groundwater

Groundwater supplies are often tested for the same parameters as surface water supplies, including coliform and thermotolerant coliform testing for detection of faecal contamination. As has already been discussed the presence of thermotolerant coliforms indicates the presence of faecal contamination and the potential presence of pathogens. Absence of thermotolerant coliforms,
however, does not necessarily ensure that pathogens are absent. Enteric viruses, pathogenic bacteria such as *Yersinia* sp. (Lassen, 1972) and protozoan parasites have been found in groundwater (generally in large volume samples), while tests for *E. coli* (generally small volume samples) were negative.

Differences in attachment rates and survival lead to differences in the ability of microorganisms to travel long distances through the aquifer. In aquifers of fine-textured soil that are vulnerable to faecal contamination from human waste, the risk of penetration of enteric viruses through the soil is higher than for bacteria and parasitic protozoa. This is because of their small size and low attachment rates, and means that bacteriophages are the most suitable parameters for assessing the contamination of the abstraction well. In coarser or fractured soils, bacteria and protozoa can travel long distances and the persistence of protozoa such as *Cryptosporidium* sp. make these pathogens critical for groundwater source quality. Spores of *Clostridium perfringens* have been suggested as an index for these persistent pathogens (as outlined earlier). Estimates based on spores of *C. perfringens* will be conservative, because of their smaller size (1 µm versus 4 µm for oocysts) and their even greater persistence in the environment (Hijnen, unpublished data). The use of spores of sulphite-reducing clostridia as an approximation of *C. perfringens* spores is less appropriate in groundwater systems as (anaerobic) soil is a natural habitat for *Clostridium* spp.

If surface water is a potential source of groundwater contamination, the presence of freshwater algae in well water suggests that biological particles of this size (and thus also protozoan parasites, viruses and bacteria) may pass the soil and contaminate the abstracted water. This was demonstrated in a survey in the USA. Moulton-Hancock *et al.* (2000) showed that the presence of aquatic microbiota was a significant predictor of the presence of *Cryptosporidium* sp. and *Giardia* sp. The microbiota included algae, rotifers, fungi, arthropods, colourless flagellates, nematodes, amoebae and gastrotrichs. It was found to be possible to differentiate between high, moderate and low risk groundwaters on the basis of the quantity and composition of the microbiota present. They suggested the use of a presence/absence test for algae as a simple tool for the prediction of the presence of *Cryptosporidium* sp. and *Giardia* sp.

The sample volumes that are used for groundwater monitoring are usually low (100 ml, despite recommendations to use larger volumes – Fujioka and Yoneyama, 2001) and the sampling frequency is generally not high (weekly - monthly). The application of larger volumes and/or increased frequency and sampling of individual wells/adits increases the sensitivity of tracing faecal contamination. The monitoring programme should not only cover regular
sampling, but also be designed to examine high risk factors, such as rainfall or the presence of vulnerable sites within the groundwater abstraction system.

4.5.2.1 Turbidity and temperature profile

Non-microbial parameters can also be used for groundwater monitoring and give information about potential risks. Turbidity peaks in groundwater may originate from soil material, but also from the rapid ingress of surface water, run-off or surface percolate. Temperature measurements at different depths in boreholes can give information about the characteristics of the major inflows and rapid changes in temperature call for further investigation, such as examination for \textit{E. coli}, \textit{C. perfringens}, faecal streptococci and bacteriophages. This is especially important in poorly confined karst and fractured bedrock aquifers, where it is very difficult to predict flow paths. The major virtue of turbidity and temperature measurements is that they can be used on-line and in individual wells. If these indicate a risk event, they can be used to trigger both further investigations and control measures (shutdown of well, redirection of abstracted water, increased treatment).

4.5.2.2 Pathogens as self-indicators

Several groundwater surveys for pathogens have been conducted in the USA. Keswick and Gerba (1980) found enteric viruses in groundwater wells in concentrations of 1.2 plaque forming units (pfu)/l. In a nation-wide study in the USA, 150 wells from various States and aquifer types (70 consolidated, 34 bedrock, 46 unknown) were sampled and analysed for the presence of viruses and bacteriophages (Abbaszadegan \textit{et al.}, 1999). Enteroviruses were found in 8.7% of the samples with cell culture and 27% of the samples using polymerase chain reaction (PCR). Hepatitis A was found in 8.0% and rotavirus was found in 12% of the samples (both using PCR methods). No correlation was found between enterovirus detected by cell culture and any of the other microbial indicators tested. These high prevalence rates indicate that virus contamination of groundwater is a greater public health concern than was formerly anticipated (Sobsey, 1999).

\textit{Cryptosporidium} sp. and \textit{Giardia} sp. have also been used to assess the contamination of groundwater systems. Hancock \textit{et al.} (1997) found \textit{Cryptosporidium} sp. and/or \textit{Giardia} sp. in 12% of 463 groundwater samples from 199 sites in 23 American States. Infiltration galleries, adits and horizontal wells were most frequently contaminated with these parasites, but they were also found in springs and vertical wells. The mean concentration of \textit{Giardia} sp.
cysts in positive wells was 8.4/100 l (maximum 120/100 l). For *Cryptosporidium* sp., the mean concentration was 5.1/100 l with a maximum of 45/100 l.

### 4.6 Summary and outlook

This chapter has illustrated the different ways to:

- Localise and characterise the sources of faecal contamination in a catchment area; and
- Determine the (variability of the) microbial quality of source water of both surface water and groundwater systems. The objective of these activities is to collect information to substantiate and support (cost-effective) approaches to management of the risk of waterborne disease.

Several developments in recent years are providing new tools to help in the localisation of contamination sources and especially in understanding the significance of the sources. One of these developments is the integration of hydrological modelling and microbiology to construct transport models that describe and predict the fate of pathogens in both surface water and groundwater catchments (Schijven and Hassanisadeh, 2000; Deere et al., 2000). This area is still in the early stages of development, but may significantly improve our understanding of the fate and ‘behaviour’ of pathogens and microbial parameters in the aquatic environment. The use of these models also forces researchers to focus more on the processes that govern transport and fate, rather than descriptive research on occurrence. A related development is the application of geographical information systems to localise sources and to relate contamination to waterborne outbreaks (Rose et al., 2000) or to drinking water contamination events.

Microbial and non-microbial parameters provide a wide range of possibilities for measuring water quality changes and for the detection of faecal pollution. When these parameters have been used to their limit, pathogen detection may provide interesting, but difficult to interpret, data (Allan et al., 2000). Developments in molecular microbiology (see Chapters 7 and 8) have provided methods that make it possible to detect these pathogenic microorganisms in water even those, such as Norwalk-like viruses, that could not previously be detected and analysed. These methods can be more specific and allow the differentiation of pathogenic and non-pathogenic strains and also allow genetic fingerprinting which is useful for identifying sources of contamination.
Similarly, the developments in (computer) technology have improved the automation of on-line measurements of water flow, temperature and turbidity. This is particularly helpful for rapid response, as illustrated by the case study from Melbourne Water, where this type of monitoring is used to divert the flow of contaminated streams away from the reservoir during storm events.

These new tools are refining the information available from monitoring surveys and they are also refining and accelerating the ability to respond to adverse conditions in a catchment or source water. It should not be forgotten, however, that much of the information that is needed to design a catchment protection strategy can be derived from a sanitary survey and that risk events can be deduced from simple parameters such as rainfall, river flow and turbidity. This information can be refined by monitoring for a set of microbial indices of faecal pollution or specific pathogens to obtain data on their occurrence in source water for the design of cost-effective treatment systems.
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